# DETECTION OF THE GRAVITATIONAL REDSHIFT OF THE CESIUM FREQUENCY STANDARD AT CRL

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Abstract

***We have detected the gravitational redshift of a Cs frequency standard that has been transported from CRL Tokyo headquarters, at an altitude of 80 m, to Mt. Ohtakadoya LF standard frequency station, located at an altitude of 794 m, about 250 km far from the CRL Tokyo headquarters. In the Mt. Ohtakadoya LF station, three Cs clocks are equipped to be the references of standard frequency radio signal emission, and they are linked with UTC(CRL) by the GPS common-view time transfer. By using this link, we can compare the frequency of any standards in CRL Tokyo and the Mt. Ohtakadoya LF station with UTC(CRL). An HP5071A Cs frequency standard with a normal tube has been transported by car from the CRL Tokyo headquarters to the LF station on 27 April 2000. After the transport, we observed that the frequency of the Cs standard became higher by about 4.6 $\times 10^{-14}$. According to General Theory of Relativity, a 700-m altitude difference will cause a 7.8 $\times 10^{-14}$ frequency difference. Considering the stability of the Cs standard and the accuracy of time transfer, the observed frequency shift shows an agreement with the theoretically predicted gravitational redshift.***

## INTRODUCTION

Detection of the relativistic effects by using portable atomic clocks has been conducted by many groups [1,2]. Today, there is little few significance in such measurements for the test of relativity. The theory of General Relativity has been tested in many cases and it is recognized as the reliable fundamental theory of precise space-time measurements within today's measurement accuracy [3]. Still, the detection of such effects would be important to prove the accuracy and stability of a system.

Recently, CRL has constructed a new LF frequency standard station at the top of Mt. Ohtakadoya, 250 km far from the CRL Tokyo headquarters and the altitude of that is 794 m. The LF station is equipped with three normal-tube HP5071A clocks, and a TTR-6 GPS receiver. In December 1999, one of the Cs standards went wrong and we fixed it. After that, we had watched the performance of this Cs standard for more than 1 month and then we transported the clock from the CRL Tokyo headquarters to the Mt. Ohtakadoya LF station. We call this clock Cs#28.

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The altitude difference between these stations is about 700 m. These conditions seemed enough to detect the gravitational redshift. Following the precedents, we tried to detect the gravitational redshift of the frequency of Cs#28 from our regular time comparison data. In this paper, we will show the result of the frequency shift measurement.

## GRAVITATIONAL REDSHIFT

The proper time of the atomic clock changes according to the gravitational potential where it placed. As the result, in the case of the transported clock near the earth's surface, the gravitational redshift is

$$\Delta f/f = 1.1 \times 10^{-16} \Delta h \tag{1}$$

where $\Delta f/f$ is the fractional shift of the frequency in Hz and $\Delta h$ is the altitude difference between before and after the transport [3].

The clock room in CRL Tokyo is at an altitude of 80 m. That in the LF station is at an altitude of 790 m. The difference between them is about 710 m. Therefore, the expected gravitational redshift of the frequency is $7.8 \times 10^{-14}$.

## EQUIPMENT AND ENVIRONMENT OF EACH STATION

### CRL Tokyo Headquarters

At CRL Tokyo, we have nine HP5071A commercial cesium clocks with high-performance tubes. Using these clocks, we generate the synthesized atomic time scale UTC(CRL) that is used as the reference of the TTR-6 at CRL. The time difference between UTC(CRL) and every clock is measured every 4 hours. These measurement data are taken in a workstation and used as the basis of the calculation of the synthesized atomic time. In the clock room, the temperature and the humidity are kept to be 26 degrees and the 50 %, respectively. The room is equipped with an electromagnetic wave shield to shut down the intrusion of unfavorable perturbation.

### Mt. Ohtakadoya LF Station

At the LF station, we usually have three HP5071A cesium standards with normal tubes. One of them is selected as the master clock in the station, while others are used as backup clocks. Here we denote the master clock as MC(LF). As at the Tokyo headquarters, the time difference between MC(LF) and other cesium clocks are measured every 4 hours. MC(LF) is also used as the reference of the TTR-6 GPS receiver in the LF station. The receiver is set to measure the GPS time according to the same BIPM schedule as at CRL. In the clock room of the LF station, the humidity is kept to be 50%, the same as that at the Tokyo headquarters. On the other hand, the temperature of that is 26 degrees, 3 degrees higher than that at the Tokyo headquarters. The station is equipped not only with an electromagnetic wave shield, but also a static magnetic shield.

### Transport

On 27 April of this year, we transported the clock Cs#28 from the CRL headquarters to the Mt. Ohtakadoya LF station. The distance between them is about 250 km. The clock was transported by car. It took 6 hours from Tokyo headquarters to the LF station. During that transport, a battery was provided so that the clock could be kept working without any discontinity.

## ESTIMATION OF FREQUENCY SHIFT

Using these data of the measurement and time transfer link, the frequency deviation of Cs#28 at each period and, thus, the frequency shift were obtained. Figure 3 shows the fractional frequency deviation of CS#28 from UTC(CRL), measured at CRL Tokyo in April before the transport. On 17 and 18 April, we put Cs#28 to the frequency tuning test. The effect of that test was apparent after a period. It is also shown that after the test, the frequency recovered to be the same as that before the test. Eliminating this period, the average deviation between CS#28 and UTC(CRL) is -14.3 $\times 10^{-14}$.

In this period, GPS common-view link data show that the fractional frequency deviation of UTC(CRL) from MC(LF) is -5.0 $\times 10^{-14}$ (Figure 4). Hence, the deviation of Cs#28 from MC(LF) before the transport is -19.3 $\times 10^{-14}$. Figure 5 shows the GPS common-view link between UTC(CRL) and MC(LF). On 3 May, we steered the frequency of UTC(CRL) by 2 $\times 10^{-14}$. In the GPS common-view link, this steering is appeared as a frequency change of 1.8 $\times 10^{-14}$. So it seems that the accuracy of the link would be a few parts in $10^{15}$.

The fractional frequency deviation of Cs#28 from MC(LF) after the transport is shown in Figure 6. It seems that it took about 2 weeks until the frequency of Cs#28 settled. The average deviation after the period is -15.7 $\times 10^{-14}$.

In addition to these frequency deviation measurements, we measured the frequency shift of a normal-tube HP5071A due to temperature variation. So far, we have obtained the typical temperature coefficient for a normal-tube HP5071A of -3 $\times 10^{-14}$ per 10 degrees (Figure 7). This result is obtained by a few days' measurements at each temperature. So it seems we have to confirm the measurement of the coefficient in the longer period. As far as we adopt this result, we can expect that the frequency shift due to the temperature variation of 3 degrees is expected to be about -1 $\times 10^{-14}$.

For the evaluation of the uncertainty of the measurement, we use the Allan variance of the Cs standards. In the case of the frequency stability between UTC(CRL) and normal-tube HP5071A, the Allan variance in a 5-day average period is observed to be about 2 $\times 10^{-14}$. That between two normal-tube HP5071As would be a bit worse, about 2.5 $\times 10^{-14}$. The uncertainty of the GPS common-view link is much less than that, so that we can neglect it here. Using these values, we estimate that the total uncertainty in the frequency measurement would be 3.2 $\times 10^{-14}$.

## CONCLUSIONS AND DISCUSSION

Using the frequency deviations shown in the previous section, the result of the frequency shift of Cs#28 after the transport to the LF station is

$$-15.7 \times 10^{-14} - (-19.3 \times 10^{-14}) - (-1 \times 10^{-14}) = +4.6 \times 10^{-14}. \tag{2}$$

Considering the total uncertainty of 3.2 $\times 10^{-14}$, this result of the frequency shift seems to be consistent with the theoretical value of 7.8 $\times 10^{-14}$, though it is not such good agreement. Some factors are considered as problems of this trial. Just about 10 days before the transport, the frequency tuning test was conducted. Also, frequency steering of UTC(CRL) was conducted a few days after the transport. These were mainly due to the fact that the detection of gravitational redshift was not originally planned when the clock was transported. Thus, we should plan the experiment more carefully next time. Also, we should examine the temperature effect more definitively. Furthermore, we should better check the frequency shift due to the difference of the static magnetic fields between Tokyo headquarters and the LF station. However, this shift would be small in so far as the C field servo motor of the clock works well and there is no interruption of the clock operation during transport. Therefore, in many aspects, further investigation will be needed.

However, we conclude that the link, equipment, and the environment in CRL Tokyo and the Mt. Ohtakadoya LF station are good enough for the detection of the gravitational redshift. In the future, we will have occasion to maintain or replace the clocks in the LF station. In that time we would like to continue the trial to detect the shift and to confirm the accuracy and the stability of the frequency standards system at CRL.

## ACKNOWLEDGMENTS

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[3] B. Guinot 1997, *"International report: Application of general relativity to metrology,"* **Metrologia, 34,** 261-290.

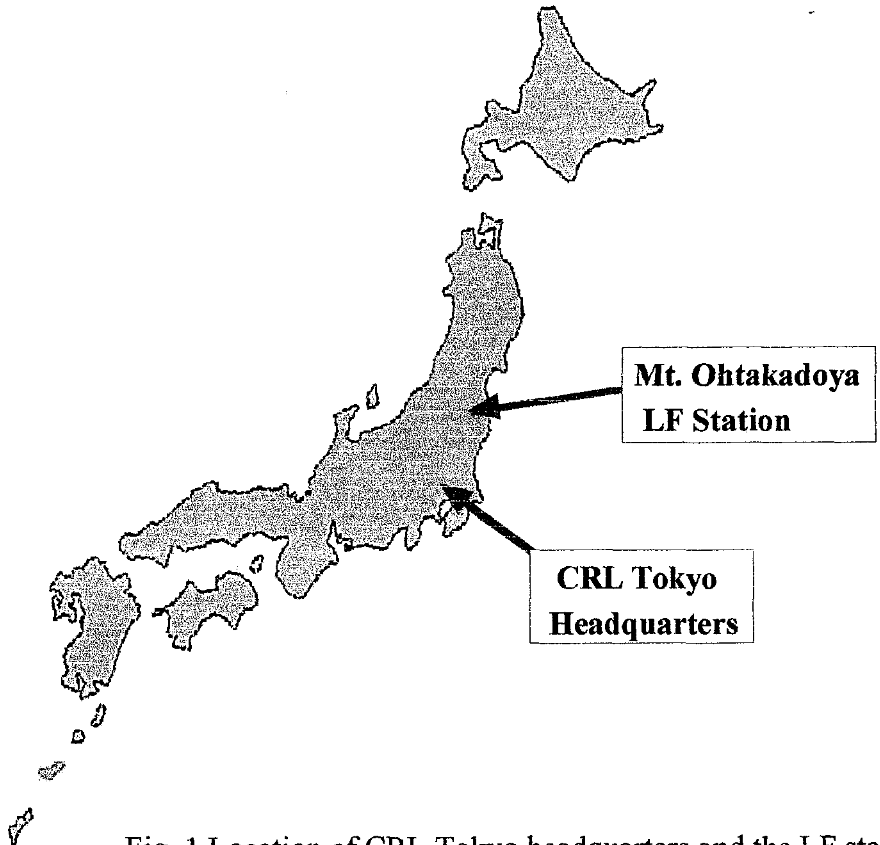



Fig. 1 Location of CRL Tokyo headquarters and the LF station

| | CRL Headquarter | LF station |
|---|---|---|
| Altitude | 80m | 790m |
| Temperature | 23℃ | 26℃ |
| humidity | 50% | 50% |
| Shield | Electromagnetic wave | Electromagentic wave and static magnetic field |
| Reference of TTR6 | UTC(CRL) | MC(LF) |

Table 1 Specifications of both stations

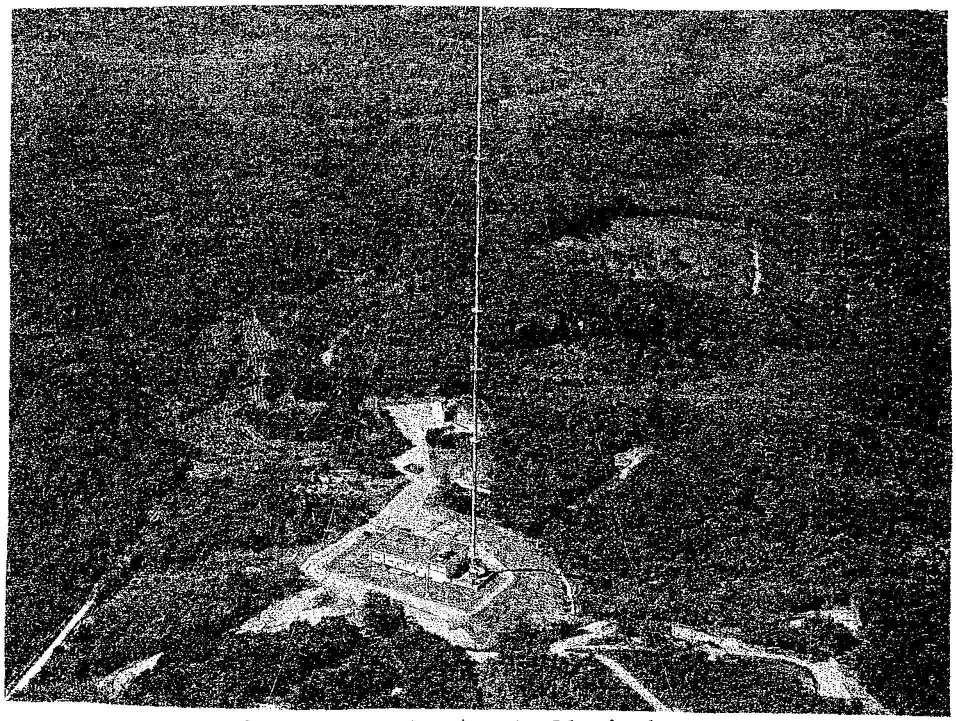


Fig. 2 LF station in Mt. Ohtakadoya

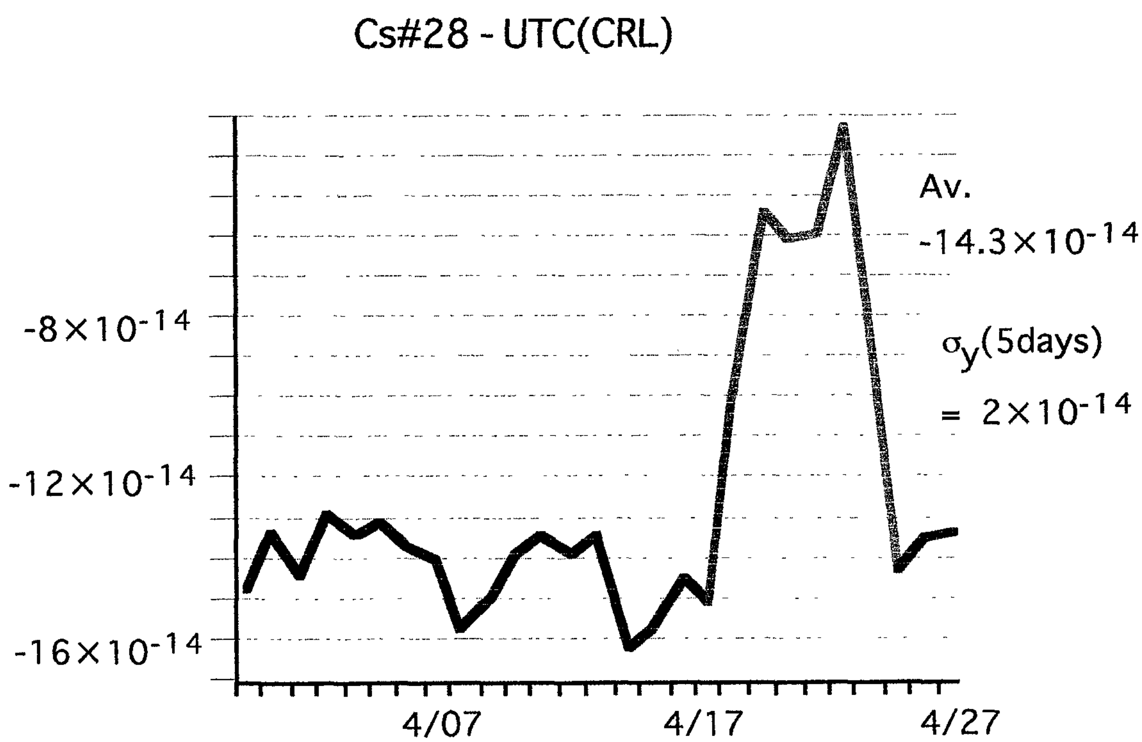
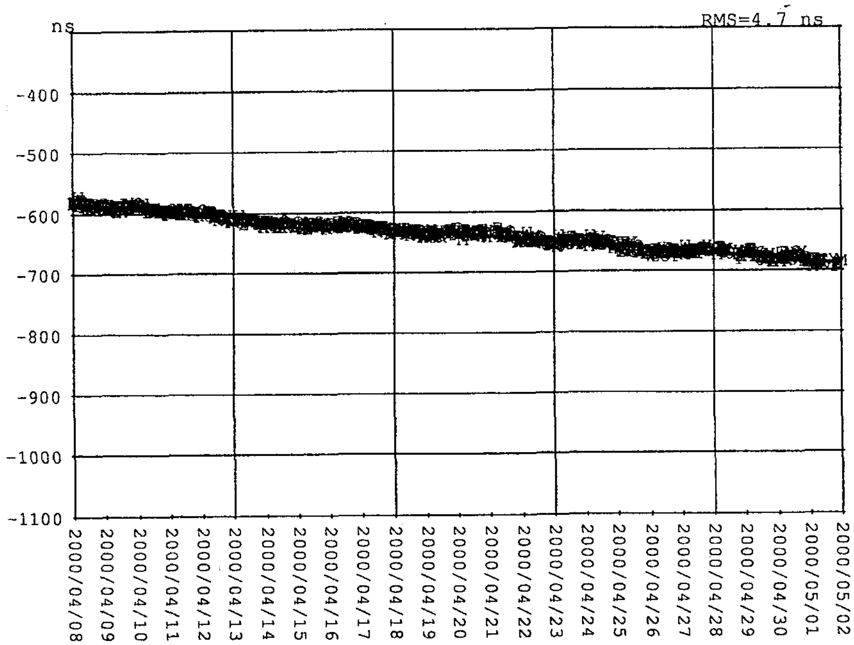
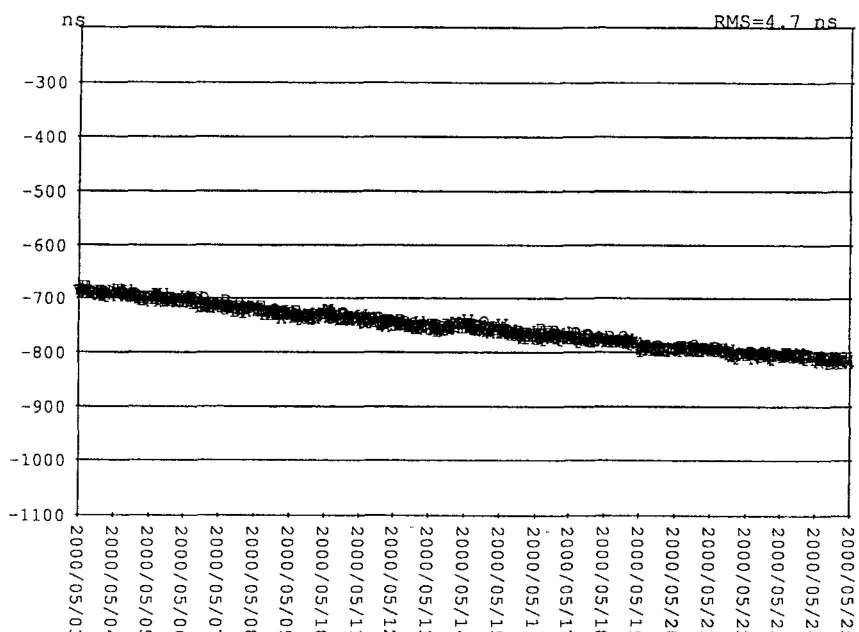



Fig. 3 Frequency deviation of Cs#28 from UTC(CRL) before transportation




$\Delta f/f$
$=-5.0\times10^{-14}$

Fig. 4 GPS common-view link between UTC(CRL) and MC(LF Stat.) in April




$\Delta f/f$
$=-6.8\times10^{-14}$

Fig. 5 GPS common-view link between UTC(CRL) and MC(LF Stat.) in May

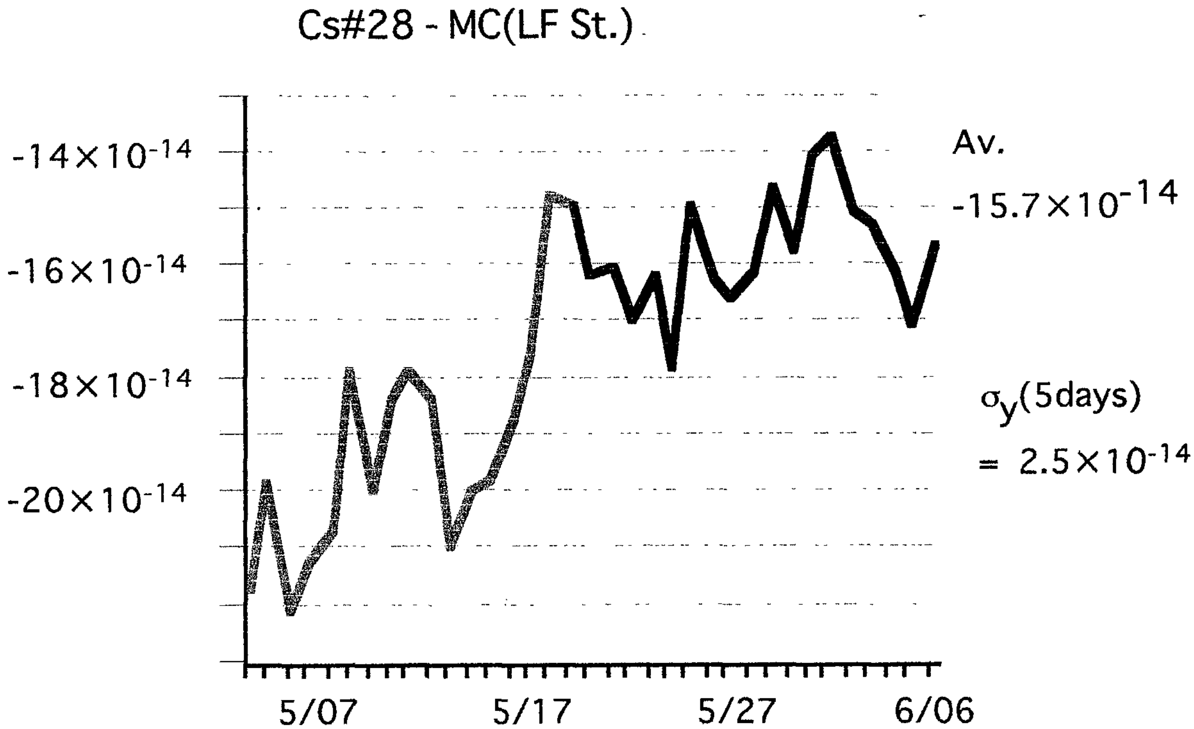



Fig. 6 Frequency deviation of Cs#28 from MC(LF) after the transportation

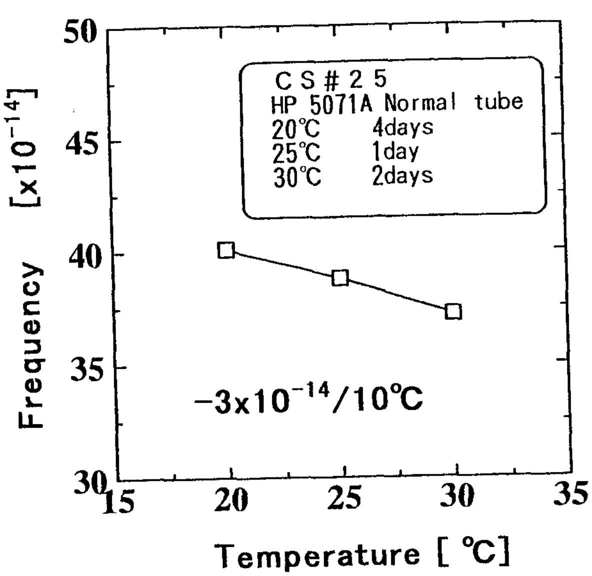



Fig. 7 Frequency shift of the same type Cs standard due to the temperature variation